THE ‘ORIGINAL’ STONE MASTIC ASPHALT:
“THE GERMAN EXPERIENCE”

Michael Kreide, BP Bitumen, Germany
Mick Budija, BP Australia, Australia
Jim Carswell, BP's Research and Technical Centre, UK

ABSTRACT

Stone Mastic Asphalt (SMA) was developed in Germany in the 1960s. SMA uses an aggregate skeleton and binder mastic to achieve superior loading capacities in heavily trafficked roads when compared with conventional asphalt mixtures. Over the last several decades it has become one of the most used asphalt pavement wearing courses in road construction and, with the expectation of increasing traffic volumes and loads, the use of SMA is predicted to increase.

The German SMA design process is based on the careful selection of appropriate aggregate particle grading and quality and on knowledge gained over many years of experience. In 1984 SMA was incorporated into the German technical specifications as a standard construction process.

SMA exhibits superior properties in several key areas when compared with conventional asphalt mixtures, these being:

- Resistance to rutting due to slow, heavy and high volume traffic
- Resistance to deformation at high pavement temperatures
- Improved skid resistance
- Noise reduction over conventional alternative pavement surfaces
- Improved resistance to fatigue effects and cracking at low temperatures
- Increased durability
- Reduced permeability and sensitivity to moisture

The reasons for these positive behaviours of SMA pavement surfaces in heavily trafficked conditions can be attributed to its design principles. The higher proportion of single-sized course aggregate fractions produces a skeleton of interlocking particles and the resultant mechanical interlock is very effective at resisting permanent deformation. The gap-graded principle of SMA also allows for the voids between the coarse aggregate particles to be filled with mastic comprising a relatively high binder content, stabilising additives and filler. The mastic increases the cohesion, resistance to moisture sensitivity and resistance to fatigue and improves the durability of SMA surfaces.

The global uptake of SMA technology in pavement surfacings has seen the implementation of a wide variety of different interpretations of the original German SMA concept. This paper will give an overview of the German experience from the selection of materials, through to design, production and laying of the mixture and will demonstrate why the original German SMA concept has become the most used asphalt mixture for high trafficked roads in Germany. Local Australian practice in the design and application of SMA mixtures will be compared with the German approach.

INTRODUCTION

Stone Mastic Asphalt (SMA) was developed in Germany in the 1960s. At the time, studded tyres were in widespread use over the winter months and they had the effect of abrading the existing surface course. Various attempts to repair the abraded material involved using a range
of proprietary materials and eventually successful products were grouped under a generic name 'Splittmastixasphalt'. SMA uses an aggregate skeleton and binder mastic to achieve superior loading capacities in heavily trafficked roads when compared with conventional asphalt mixtures. Over the last decades it has become one of the most used asphalt pavement surface courses in road construction in Germany and, with the expectation of increasing traffic volumes and loads, the use of SMA is predicted to increase.

Since the 1980s SMA technology has spread to other countries in the world, although it should be said that the original design principles developed in Germany have not always been followed. The German SMA design process is based on the careful selection of appropriate aggregate particle grading and quality and on knowledge gained over many years of experience. In 1984 SMA was incorporated into the German technical specifications as a standard construction process.

The global uptake of SMA technology in pavement surfacing has seen the implementation of a wide variety of different interpretations of the original German SMA concept. This paper gives an overview of the German experience from the selection of materials, through to design, production and laying of the mixture and will demonstrate why the original German SMA concept has become the most used asphalt mixture for high trafficked roads in Germany. Local Australian practice in the design and application of SMA mixtures is compared with the German approach.

STONE GRANULATES

German SMA consists of a mineral aggregate mixture (coarse aggregates, crushed sand and filler) with a very high content of stone aggregates and a high proportion of the respective largest aggregate size [1]. The mineral aggregates are described more fully in reference [2]. The mixture is essentially gap-graded and has an extremely stable aggregate skeleton.

Stone aggregates for road construction

The German requirement for aggregates is that they must be extracted and prepared in such a way, that they exhibit consistent characteristics and satisfy the requirements of TL Min – StB [3]. In accordance with [3] the following essential requirements are specified.

Supplied granulates and permissible highest values for over and undersized aggregates

In the case of the supply of aggregates a distinction is made between the unbroken stone granulates of natural sand and chippings, the crushed stone granulations of crushed sand, stone aggregates and ballast, high grade crushed sand and high grade stone aggregates. Filler is defined as a supplied granulate in the aggregate size classification 0/0.09 mm, including any portion of oversized aggregates present. It is critical that aggregates of high quality are used in SMA mixtures and in Germany, for the highest category roads, crushed rock is preferred as it provides the necessary strength characteristics. Further, their angular shape encourage a greater interlocking strength. For the lower volume roads, proportions of natural sand that are more rounded in nature may be included, but they are regulated according to the German specification (Table 1).

Aggregate Shape

As a rule, the aggregate shape is assessed visually. The proportion of the aggregates, for which the ratio of length to thickness is greater than 3:1, must be:
For high-grade stone aggregates over 5 mm, a maximum of 20 % by mass of the supplied granulate.
In common with most asphalt mixtures, shape is an important requirement. In SMA mixtures, the aggregate skeleton is key to achieving a deformation resistant mixture. Mixtures containing too many 'flaky' aggregates are more likely to slide relative to one another, causing the aggregate skeleton structure to break down under traffic loading.
Resistance of stone aggregates to polishing

Depending on the specific application, high quality stone chippings, which are used for surface layers and coatings, must have a high resistance to polishing (PSV). In the polishing test [3] defined aggregates are subjected to a time-accelerated polishing process. The polishing coefficient (PSV) is then measured and the polishing coefficient must be:

- 43 for roads in construction classes III-VI with normal loading
- 50 for roads in construction classes SV, I and II and for roads in construction class III with special loading.

For surfaces on highways with special long term and severe polishing wear loading, aggregates are recommended with PSV values greater than 53.

Mixture Design

The secret to good SMA mixtures lies in the design procedure. The most important aspect is that SMA mixtures are designed to meet volumetric criteria. The design process is one of adjusting the grading to accommodate the required binder and voids content rather than the normal procedure of adjusting the binder content to suit the aggregate grading. It is for this reason alone that many so-called SMA materials laid outside of Germany would NOT be considered true SMA mixtures because they fail to adopt this crucial design approach.

Table 1: Table 4.1 SMA - ZTV Asphalt-StB

<table>
<thead>
<tr>
<th>SMA</th>
<th>0/11 S</th>
<th>0/8 S</th>
<th>0/5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mineral Aggregates</td>
<td>Pure grit, crushed rock, rock dust</td>
<td>Pure grit, crushed rock, natural sand, rock dust</td>
<td></td>
</tr>
<tr>
<td>Aggregate Size mm</td>
<td>Passing &lt;0.09 mm M.-%</td>
<td>Retained ≥2.00 mm M.-%</td>
<td>Retained &gt;5.00 mm M.-%</td>
</tr>
<tr>
<td></td>
<td>0/11</td>
<td>0/8</td>
<td>0/8</td>
</tr>
<tr>
<td></td>
<td>9 - 13</td>
<td>10 – 13</td>
<td>8 - 13</td>
</tr>
<tr>
<td></td>
<td>73 - 80</td>
<td>73 – 80</td>
<td>70 - 80</td>
</tr>
<tr>
<td></td>
<td>60 - 70</td>
<td>55 – 70</td>
<td>45 - 70</td>
</tr>
<tr>
<td></td>
<td>≥40</td>
<td>≤10</td>
<td>≤10</td>
</tr>
<tr>
<td></td>
<td>≤10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1:0</td>
<td>1:0</td>
<td>≥1:1</td>
</tr>
<tr>
<td>2. Binder</td>
<td>Binder type</td>
<td>50/70 (PmB 45)*</td>
<td>50/70 (PmB 45)*</td>
</tr>
<tr>
<td></td>
<td>Binder content M.-%</td>
<td>≥6.5</td>
<td>≥7.0</td>
</tr>
<tr>
<td>3. Stabilisers</td>
<td>% by mass of mixture</td>
<td>0.3 - 1.5</td>
<td></td>
</tr>
<tr>
<td>4. Mix (laboratory)</td>
<td>Marshall Test Piece</td>
<td>135 ± 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Voids Content Vol.-%</td>
<td>3.0 - 4.0</td>
<td>3.0 - 4.0</td>
</tr>
<tr>
<td>5. Placement</td>
<td>Thickness of application cm</td>
<td>3.5 - 4.0</td>
<td>3.0 - 4.0</td>
</tr>
<tr>
<td></td>
<td>Weight of application kg / m²</td>
<td>85 - 100</td>
<td>70 – 100</td>
</tr>
<tr>
<td></td>
<td>In exceptional circumstances, e.g. on an uneven surface:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickness of application cm</td>
<td>2.5 - 5.0</td>
<td>2.0 - 4.0</td>
</tr>
<tr>
<td></td>
<td>Weight of application kg / m²</td>
<td>60 - 125</td>
<td>45 - 100</td>
</tr>
<tr>
<td></td>
<td>Degree of compaction %</td>
<td>≥97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Voids content Vol.-%</td>
<td>≥6.0</td>
<td></td>
</tr>
</tbody>
</table>

*Only in certain cases
** When using PmB 45, Marshall test pieces must be manufactured at 145±5°C
Of particular note is the minimum binder contents required for the various grading types. It is known that many 'SMA' mixtures laid outside of Germany have lower binder contents. It would be more consistent to call such materials 'high stone content asphalts' rather than SMA. Table 1 shows the German specification. The aggregate gradings, corresponding to Table 1 are shown in Figures 1, 2 and 3. The design process involves the following stages:

1. Trial mixture, complying with the grading envelope, is made using the chosen aggregates
2. Laboratory mixtures are made at the target grading and at the minimum binder content.
3. Drainage behaviour is assessed
4. Marshall specimens are made to assess voids content. If the requirements of Table 1 are not met, then the priority change order is:
   - Coarse aggregate grading or content
   - Content and/or filler type
   - Content and/or stabilising additive
   - Binder content
5. The target composition is then adopted as the job material specification

**BINDER CARRIERS – STABILISING ADDITIVES**

German SMA consists of high grade stone aggregates with a high proportion of quality crushed aggregates, filler and bitumen (paving grade bitumen or preferably polymer-modified bitumen). In order to absorb the relatively high binder content without drainage, stabilising components are added to the asphalt.

**Stabilising additives**

Hutschenreuther and Wörner [2] describe the stabilising addition chiefly as a binder carrier, which has the function of stabilising the homogeneity of the asphalt and preventing draindown of the binder. The following materials can be used as stabilising additives:

* Organic fibrous materials (fine fibrillated cellulose, fibre lengths up to approx. 5000 µm, fibre thickness approx. 45 µm)
* Organic fibrous materials with bitumen casing (covered with bitumen and, for example, powdered with talcum)
* Mineral fibrous materials (obtained from a fluid melt, glass-like surface is sized to improve the adhesion of the bitumen)
* Silicic acid
* Polymers (preferably in the form of a pre-mixed polymer-modified binder produced at a purpose-built PMB production plant)
* Siliceous earth.

Further requirements covering the quality of German SMA are described in [4] and [5]. In [4] it is stated that stabilising additives should prevent the segregation of the SMA during manufacture, transport, application and compaction. In [5], Gauer indicates the inconsistency of the terms ‘binder carrier’ and ‘stabilising additive’ and their interpretation. Furthermore, the author is of the opinion that, following application and compaction, the additive should have no further part to play in SMA, having already fulfilled its primary task. The SMA derives its strength from the structural framework of the stone aggregates and its durability from the thick binder films. The author goes on to present his investigation of SMA and concludes that stronger stiffening additives can have an influence on the characteristics of the mortar in the finished asphalt. However, the products that should be used are those that improve the characteristics of the asphalt.

The importance of using stabilising additives is demonstrated in Figure 4 where percentage binder drained is shown as a function of stabiliser addition in a 0/11 SMA having a binder content of 6.0%. However, it should be noted there is a new generation of modified binders that can be successfully used in SMA mixtures without the need for binders.
EFFECT OF THE ASPHALT MORTAR ON THE CHARACTERISTICS OF STONE MASTIC ASPHALT

German technical literature describes best practice in SMA design. In his dissertation [6] Herr describes the asphalt mortar as a mixture of bitumen, stone dust < 0.09 mm, fine sand < 0.09 mm and additives if required, which are present to prevent the draining off of the binder.

The dissertation provides a further discussion on the influence of the asphalt mortar on the resistance to deformation of the SMA. Research of German practice revealed that the theme has thus far only been treated in an outline manner. The mortar has the task of ‘cementing’ the stone grains of the stone granulate. A minimum quantity of asphalt mortar is required for this. In addition, the asphalt mortar should be as viscous as possible, in order to improve the resistance to deformation. Several publications proceed on the theme of the draining off of the binder agent. The ‘drain-off test’ of Schellenberg/von der Weppe has been cited as a demonstration criterion. This drain-off test provides information on the demixing tendency of SMA.

A strong influencing parameter for the resistance to deformation of SMA is the binder. It can be shown that the mechanical behaviour of SMA at high temperatures depends on the rheological behaviour of the asphalt mortar. However, consideration has also to be given to the binder content. Herr was also able to derive from his research that, in some cases, there were not sufficient interactions between the additive and the binder. It is clear, that high quantities of binder can only be contained in the SMA if drain-off inhibiting substances are provided to cater for storage and transport.

When using mineral fibres, their behaviour in respect of mecanical loading has to be considered in order to ensure they maintain their shape and structure (i.e. don't break down) through the handling process. The fibres used in this work can practically be rubbed away between the fingers without great exertion. This fact could certainly have had an effect on the deformation behaviour of the SMA.

Investigation has shown that the modification of the binder with polymers led to a reduction in the tendency of the SMA to deform.

Using the relationships established by Herr [6], it would therefore be possible to assess the deformation behaviour of SMA by a simple consideration of the binder content and the needle penetration of the asphalt mortar in relatively inexpensive preliminary investigations in the laboratory. The determination of the penetration of the mortar is a suitable method of assessing the characteristic quantities of the asphalt mortar on asphalts, particularly in SMA, at high usage temperatures. The penetration of the mortar has to be determined at 40° C with a 200 g load. This method could yield an initial result after just a few hours, which could then be used as a basis for a further optimisation of the SMA at high usage temperatures.

SELECTION OF A SUITABLE BINDER

Due to economic growth and an extensive removal of the barriers to travel in Europe, heavy traffic is on the increase [7]. In many cases there is also an increase in axle loadings. The combined effects of the climate and traffic lead to continually increasing loading of the strategic transportation routes. To satisfy the attendant requirements, polymer-modified binders are being used more frequently in the production of asphalt. In many cases on highly loaded roads the use of conventional paving grade bitumens is no longer adequate. Through the use of polymer-modified binders, stiffer binders can be used, which do not lead to the formation of cracks at low temperatures. This effect can be clearly demonstrated by comparing the plasticity ranges (difference between the ring and ball softening point and the breaking point (Fraaß)) of paving grade bitumens and polymer-modified binders. The softening point represents the behaviour of the binder at summer temperatures and the breaking point (Fraaß) represents the behaviour at winter temperatures. The addition of polymers has the effect of extending the plasticity range on both sides. The behaviour under both hot conditions (summer) and cold conditions (winter) is improved by the modification with polymers satisfying the requirements. The advantages of
polymer-modified binders in comparison with paving grade bitumens can be summarised as follows:

- Better resistance to heat
- Better behaviour under cold conditions
- Better adhesion to the stone
- Better cohesion
- Better fatigue behaviour.

In the modification of bitumens with polymers it is principally the elastomeric PmBs that have come to the fore in Germany.

The elastomers influence the elastic behaviour of the bitumen and also increase the viscosity. The marked elasticity can be measured in the form of the elastic recovery of a previously elongated bitumen test piece. The plastomers influence the viscosity of the binder via their melting point. Up to the melting point they have the effect of increasing the viscosity and thereafter the viscosity is reduced.

An important criterion for ready to use polymer-modified bitumen (PmB) is its stability during storage. Bitumens and polymers should form a homogeneous whole and not separate during transportation, storage and processing.

The proportion of polymer-modified bitumens in Germany in 2002 is about 14 percent of the overall use of bitumens in road construction (estimated at 330,000 tonnes) and has more than tripled since 1990. The ever increasing loading of the road network will mean that the application of polymer-modified bitumens will continue to increase in the future.

The first specification for PmB, the “Technical conditions for the delivery of ready to use polymer-modified bitumens” was introduced in 1991 [8a]. It became necessary to revise the specification of 1991, since the requirements for the binder had been extrapolated and new types had been incorporated. In addition, the first requirements for higher polymer-modified bitumens had been formulated [8b]. Polymer-modified bitumens are those described in DIN EN 12597 [9], whose rheological characteristics are modified during manufacture through the use of one or more organic polymers.

MANUFACTURE, TRANSPORT AND APPLICATION

Manufacture

German practice in the mixing of asphalt is covered in accordance with the “Additional technical contractual conditions and directives for the construction of roadway surfaces from asphalt” [4] and the associated “Code of practice for qualification tests on asphalt” (1998 issue, [4a]).

The material flow into the mixing hopper must take place in the sequence given below in order to ensure adequate dispersal of both the filler and the fibre throughout the mixed material and to obtain a fully coated mixture. The mixing times are slightly longer than for conventional asphalts because of the inclusion of the fibres. The order, together with approximate timings are:

Coarse and fine aggregates introduced and mixed over a 15 seconds period
Filler introduced and mixed over a 20 seconds period beginning at the same time as for the coarse and fine aggregates
The fibres are also introduced during this dry mixing time, the exact timing being dependent on the fibre type but early enough during the cycle to ensure full dispersion but not so long as to break down the fibre.
After the dry mixing time of 20 seconds, the binder is introduced and mixed with the 'dry' components over a 15 second period
There then follows a further 10 seconds mixing cycle followed by an 8 seconds discharge time
Most SMA is produced in batch mixing plants with pug-mill mixers, although continuous (drum) mixing plants can be used. In the latter case, pelletised fibres should be used and extreme care is required to ensure an even distribution of the various components throughout the mixing process. Quality production control is an essential requirement to ensure the volumetric proportions are maintained.

**Transport**

In addition to the manufacture of the bituminous asphalt mixture in the mixing plant, special significance is attached to the transport of the material to the point of application. Normally the bituminous asphalt mixture is transported in a heavy goods vehicle covered with tarpaulins (double-sheeted) and/or in a heat-insulated vehicle.

Covering the hot asphalt mixture should prevent damage to the bitumen as a result of oxidation due to the effect of the oxygen in the airflow during transportation, because otherwise there is the possibility of a hardening of the bitumen equivalent to up to 2 binder type gradings. This is then associated with a negative effect on the cohesive behaviour of the bitumen on the mineral material. Furthermore, rapid cooling of the bitumen asphalt mixture should also be avoided, particularly in unfavourable weather and long transportation times, as should also the ingress of water into the hot mixture. In fact, in city road construction, where relatively low quantities of asphalt are involved and work progresses more slowly, the use of heated HGV containers and insulated trailers with horizontal belt conveyors have proved to be particularly advantageous.

It is a mistake to believe that the cooling of the bitumen asphalt mixture over long transportation routes can be compensated for by the use of excessive mixing temperatures.

**Application**

In the German DAV manual (10), in addition to general aspects, the authors also describe the composition of the bituminous mixture, its manufacture, transportation and the application and compaction of SMA. The manual is a useful guide for the client, the asphalt producer and the contractor applying the product. The following recommendations are given for manufacture, storage and transport:

- When preparing the qualification test, a voids content of 3.5 Vol-% should be targeted in construction classes SV and I. In all other cases, and when using a PmB, a value of approx. 3.0 Vol-% is required.
- The total coarse aggregate content has been reduced from 75 to 73 % by mass. This contributes to a better homogeneity in the mixture.
- The mixing times during manufacture should be provided after taking account of the addition of cellulose fibres. It is important that adequate pre- and post-mixing times are available for full effectiveness of the pellets. It is recommended that the liberation and homogenisation are checked from time to time.
- As a rule, and as in the case of other types of asphalts, SMA mixtures should not be immediately stored in the loading silo for long periods, otherwise damaging changes in the binder may occur.
- The loading areas in the transport vehicle must be clean. Only a suitable anti-sticking agent must be used. Diesel is not permitted.
- Even in summer, the transport vehicle must be covered with windproof tarpaulins to avoid cooling off of the mixture and damaging oxidation of the binder as a result of contact with the oxygen in the air.
- Heat insulated HGV containers and trailers with horizontal belt conveyors have proved their value in the case of low application quantities and where the progress of work is slow, or when maintenance/repair procedures are liable to interrupt the application.

The following rules are given for application and compaction:

- The temperature of the mixture in the finisher hopper should be as uniform as possible, i.e. no cold accumulations of the mixture in corners and crevices.
The road finisher that is used should be adjusted to the speed of application, such that an appropriate level of precompaction is achieved, i.e. it should not be too high. Basically, the rolling operation should follow soon after the finisher. A minimum of two rollers is required for each application track. The compaction should be achieved with heavy tandem or three-wheel rollers (service weight > 9 t). Vibration compaction should only carried out at sufficiently high mix temperatures and after static compression. Vibration should not be used if the layer temperature is below 100°C. As a rule, vibration should not be used in the case of a rigid foundation (e.g. concrete) and for course thicknesses of less than 2 cm, since this can lead to loosening of the foundation and a break up of the aggregates. Rubber wheel rollers are ineffective for the compaction of SMA. They are counter-productive under certain circumstances and are no longer used. Any additional manual operations (hand-laying) with SMA should be carried out quickly and without delay and, if possible, at the same time as the application with the finisher. The roller compaction must be undertaken without delay after the application. A lack of precompaction by the finisher should be accounted for in the thickness of the application.

The following should be observed when treating the paved surface:
In order to increase the initial grip characteristics the precautions referred to in ZTV Asphalt-StB 01 [4] should be taken account of in the detailed estimates. The quantity (of grit) for spreading is 1 to 2 kg/m²; in addition to the 1/3 mm aggregate size, a dedusted / light bitumen coated crushed sand 0.25/2 mm has also been proven in use. If possible, 2/5 mm stone chippings should not be used due to the higher noise emission. The material to be spread can be applied either directly behind the finisher beam or between the first rollers, but in any case it must be applied to the still adequately hot and bondable surface and rolled in. A mechanical method of spreading should be employed to obtain an even surface appearance. After the application, the compacting and subsequent treatment a minimum period of 24 hours should be allowed, if possible, to allow the surface course to cool before the road is released for use by traffic.

Application during adverse climatic conditions:
Basically, application must not take place on a frozen foundation and should not take place on a wet foundation. Furthermore, the foundation must be free from snow and ice. Cold foundations are particularly detrimental when thin layers are to be applied. At air temperatures of less than +6° C the applied layer cools so fast, that it can no longer be adequately compacted.

SMA surface courses must not be laid in the rain nor on a wet surface. The damp conditions extract heat from the asphalt and it can then no longer be adequately compacted. In addition, if the adhesion of the layers is inadequate, cracks and corrugations will occur and even the formation of blowholes.

**GERMAN EXPERIENCE WITH STONE MASTIC ASPHALT**

**Experiences with SMA on Bavarian autobahns**

The summers of 1994 and 1995 [11] were extremely hot in Germany and led to a considerable increase in the formation of ruts on asphalt roads. In several Federal States road strengthening was provided, especially with SMA surface courses. In the absence of an in-depth investigation of the causes, the reason for the more pronounced development of rutting was attributed to the SMA. Either knowingly or unknowingly, it became apparent, that in recent years and for various reasons (increasing axle loadings, increase in tyre pressures, the use of 'Super-Single' tyres instead of twin tyres) an increase in the contact pressure of tyres had led to a massive increase in the shearing stresses in the binder and surface layers. On the Bavarian long distance...
roads, despite comparable heat in the years 1994 and 1995 and despite the very heavy LGV traffic, no special problems with rutting in SMA surface courses had been observed. For certain, a highly stable asphalt binder is indispensable in order to avoid the formation of ruts.

The South Bavarian Autobahn Authority uses polymer-modified bitumens as binders (as a rule PmB 45 grade) in cases of very high loading, i.e. construction class SV and I. Over the last 10 years, SMA surface layers with the correct bituminous mixture and careful manufacture have proved to be durable and stable under the most severe traffic loadings.

Noise measurements on the test section of the autobahn A 93 (Rosenheim – Kiefersfelden) have shown in addition to the high resistance to deformation, that it is possible to manufacture SMA coverings with good noise suppression characteristics, which can possibly be further improved.

**New quality criteria for standard bitumens and PmB**

It the Autumn of 1997 a working group [12] ARBIT was formed in order to discuss new test methods for binders and to prepare a quality overview on the basis of these test methods of the binders that were available on the German market.

The test programme included the binders B 65, B 45, PmB 65, PmB 45, which are used in the RStO construction classes I and SV [RStO] and described in DIN 1995 and TL PmB. Added to these was PmB 25, which at that time was not included in TL PmB. In addition to the conventional characteristic data, the following rheological test methods were considered in the programme:

- DSR at 40 – 60° C to describe the rheological behaviour and hence the resistance to deformation of a binder for use in the upper temperature range.
- BBR to characterise the low temperature behaviour.
- Force ductility to describe the tensile load/elongation behaviour and the homogeneity.
- Tensile load/retardation tests to describe the behaviour of the binder at lower temperatures.

Short and long-term ageing was carried out by means of a rotating cylinder (RTFOT), PAV and RCAT.

In addition to the tests on the binder, asphalt tests were also carried out. For this purpose those types of bituminous mixtures were selected, which are of practical relevance, which satisfy ZTV Asphalt-StB 94/98 [13] and are used for construction classes SV and I. In order to produce asphalts for the various test methods, which are as homogeneous as possible, an SMA 0/8 S and an asphalt binder 0/16 S were selected.

The following tests were carried out:

- Rut formation test in a water bath in accordance with TP A-StB [14] at 40, 50 und 60°C to assess the stability of the asphalts under load at temperature and the adhesion of the binder to the stone granulates.
- Tensile strength at +5° C, before and after storage in water, over a period of 24 hours at 60° C, to assess the adhesion.
- Axial cooling tests to assess the low temperature behaviour.
- Two-point bending tests to determine the fatigue behaviour.

The investigations showed that, for SMA, paving grade bitumens B65 are not suitable. B45 can be used for roads with low traffic loading. For higher traffic loadings, PmB 45 and PmB 25 have clear advantages and have been proved in practice.

**Assessment of stone mastic asphalt on highly loaded road sections**

In [15] Pätzold reported on the preparation of documentation on the long-term assessment of SMA on dual carriageways. On the basis of a discussion between the Federal Transport Ministry and the German Asphalt Institute (DAI), Professor Dr. Steinhoff and Professor Dipl.-
Ing Pätzold presented this documentation, in which an evaluation is made of the various methods of construction of highly loaded roads.

The data was obtained centrally via the Road Construction Administration and the Autobahn Administration for the region of Lower Saxony, Baden-Württemberg and Bavaria. As many new and renewed road routes as possible (Complete surface renewal) utilising SMA were included in the study.

An evaluation of the study yielded the following results:

- The mean value of the measured rutting depths over the period of the acquisition of data (around 10 years) was found to be between 4 and 5 mm, with a scatter of 1.5 mm. The loadings from heavy traffic and temperature (Summer 1995!) were extremely high at times.
- In more than 75% of the evaluated data the traffic loadings due to heavy traffic exceeded 4,500 vehicles in 24 hours (Highest value 18,000 vehicles/24 h).
- A trend is discerned, which indicates, that transverse unevenness increased over the period of use.
- Over the period considered in the study (maximum 10 years) the order of magnitude is only 2 mm (0.2 mm/year).

**Practical assessment of asphalt with polymer-modified bitumens**

In order to objectively test the long-term behaviour of polymer-modified bitumens (PmB) in asphalt [16], the leading manufacturers of PmB in Germany awarded a contract for an extensive programme of investigations on 10 stretches of road, which commenced in 1998.

The decisive criteria for the selection of the 10 sections of road, which had previously been trafficked over a period of between 5 and 14 years, was a high traffic loading, regional distribution throughout Germany and, if possible, the availability of initial data. The objective was to evaluate the bitumen performance of NPGs and PMBs and the performance of NPGs and PMBs in asphalt (SMA and asphalt course 0/16 S). With the exception of one poured asphalt section, the sections featured stone mastic asphalt with PmB 65 and B65 (now 50/70).

On each section examined, transverse profiles on the main traffic lanes were recorded at two representative stations and core drillings were taken from the nearside wheel tracks. In addition, core drillings (100 – 300mm) were taken between the wheel tracks to enable the investigation of the composition and characteristics of the mixed material, and the properties of the binder after recovery with toluene.

The extensive investigations showed that the use of polymer-modified bitumens enabled very stable and, at the same time, dense stone mastic asphalt surface courses to be produced. The ageing of PmB is comparable, or better, than paving grade bitumen B65. A full range of elastic characteristics have been demonstrated, even after a long period of use. The characteristics typifying the low temperature behaviour show that it is possible, with polymer-modified bitumens, to employ a binder that is a classification grade harder than paving grade bitumens, without increasing the danger of the formation of cracks.

**EXPERIENCE WITH SMA IN AUSTRALIA**

SMA usage in Australia began in 1990 when VicRoads conducted a trial in Victoria on the Princess Hwy Dandenong. A 14mm mixture mixed using a batch plant was used based on Rettenmaier design and imported Arbocell fibre; however, the trial was not fully successful. A further trial of 14mm SMA was conducted in 1993 on the Hume Hwy and Maroondah Hwy that was deemed to be successful. VicRoads have placed over 15,000 tonnes up until 1996, (no tonnage data is available after this date). Later mixtures were also conducted using 10mm gradings. The early VicRoads mixtures used C320 grade bitumen with PMB binders being introduced in 1999 for high fatigue applications.
Brisbane City Council (BCC) in Queensland trailed SMA mixes in 1992. The Rettenmaier grading was also used as their design principal for their 10mm SMA design using multigrade bitumen and manufactured using a drum mix plant. No fibre was used in these mixes. Some of the BCC mixes were considered to work satisfactorily while others did not due to the drain down of binder and the high percentage of elongated particles in the mix, with some flushing of the mix also occurring.

In 1994/1995 fibers were introduced into the BCC mixes, several types of fibers were trailed including mineral, cellulosic and glass fibers. The cellulose fibres were considered by BCC to give the best results. BCC has continued to use SMA which has constituted up to 20% of their total annual asphalt production.

The Department of Main Roads (QDMR) in Queensland has placed SMA in Queensland since September 1996. The first trial was located in the Metropolitan District on a section of Mt Gravatt - Capalaba Road, adjoining the Capalaba Bypass using a 14mm mix manufactured using a batch plant. The trial was considered successful. QDMR has produced over 1.5 million tonnes of SMA to the end of 2002. The original QDMR specification was written in 1993 and based on a combination of the Rettenmaier design, Brisbane City Council’s SMA design and the QDMR 14 mm Open Graded mix design. The QDMR SMA mix design incorporates the use of heavily modified SBS binders, typically A15E and A10E grades as specified in AP-T04 [A] with additional limited use of multigrade bitumen in the last several years.

**SMA Design**

Queensland and Victoria State Road Authorities both have issued specifications for the manufacture of SMA materials using nominal sizes 7, 10 and 14mm [18] [19]. The Australian Asphalt Pavement Association has produced a SMA Asphalt Design and Application Guide [20], AUSTROADS has published APRG Report No.18 [21] and Australian Standards has published AS2150-1995 Hot Mix Asphalt [22], which cover SMA mixes in sizes 7, 10 and 14mm.

Australia practice in SMA design is based on the use of coarse crushed aggregate particles and a mastic consisting of fine crushed aggregates, natural or crushed sands, filler, fibre and binder with a gap graded particle size distribution. The coarse aggregate particles give SMA its resistance to deformation by the aggregate skeleton created, achieving a stone on stone contact. The mastic of fine aggregate, filler, fibre and binder fills the voids between particles to enhance the SMA’s durability and resistance to water susceptibility.

**Aggregate and Fillers**

The German specification requires coarse aggregates to be of the highest quality crushed aggregate available with cubical shape, high durability and resistance to polishing. Aggregate with elongated or flat partial shape should be avoided. Typical coarse aggregate types used in Australia are basalts, granites and hornfels. The flakiness index for the coarse aggregates varies from 20-35% depending on the State or Government Authority issuing the specification. To adhere closer to the German experience the flakiness index for coarse aggregates should be no more than 20%. The aggregate degradation factor and polished stone values should be increased so only high quality aggregates are used in the manufacture of SMA as all aggregates sources are not suitable for the manufacture of SMA. In Germany, fine aggregates are required to be of the highest quality crushed aggregates, but in Australia natural sands are allowed which may adversely affect the mix stability.

**Binders and Fibres**

Binders commonly used may be conventional paving grade C320 binder, multigrade or polymer modified binder. The binder selection should suit the pavement condition and expected loading. On highly trafficked or fatigue prone pavements polymer modified binders are preferred. Fibres used in SMA are typically cellulose fibre in a pelletised form pre-blended with bitumen, or in loose form. In the early nineties several other stabilizers were trialled including glass fibre and
rock wool fibre. Recent trials using acrylic fibres have been conducted by QDMR in North Queensland.

**SMA Production and Laying**

Batch plants and drum mixing plants are used to manufacture SMA. SMA requires an increase in mixing time to ensure the fibre and fines are adequately dispersed in the mix uniformly, and that there is no balling up of the fibre and fines in the mix, this may not be possible with some of the drum mixing plants, as mixing time can not be increased or prolonged. The Australian practice of using drum mixing plants may result in fibres coming into direct contact with the heating flame and being burnt. Fibre distribution within the SMA should be monitored to ensure that even distribution of the fibre is achieved. The production of SMA should be closely monitored to ensure that all aspects of the production process are met and satisfied.

Mix production temperatures vary depending on the placement conditions and haulage distance. Mixing temperatures are generally in the range of 150 –165°C. Exceeding this range would increase the susceptibility of the mixture to binder drainage. Mix production temperatures of up to 180°C have been noted for modified binders and temperature of up to 170-175°C for non-modified binders.

The compaction process as applied to SMA in Australia differs from the compaction practice used in Germany. Compaction is commenced immediately behind the paver by heavy steel drum rollers with no vibration used. Despite the known problems, vibratory compaction and multi-tyred rollers have been used on occasions to achieve field compaction. Vibration should be avoided to achieve compaction as degradation of coarse aggregates will occur and induce bleeding of the binder to the surface. Multi-tyred rollers are not recommended as stone pickup occurs and binder can be drawn to the surface causing flushing. The multi-tyred rollers can also reduce the skid resistance of the mixture by closing up the surface texture.

Typical air voids of laid SMA surfacings are generally much higher than in Germany where air voids are typically 3.0 - 3.5%. In Victoria in the early nineties, field air voids were in the range of 6-9% although they are now in the range of 5-7%. In Queensland, SMA mixtures have produced field voids in the range of 6-11%.

The opening up to traffic of SMA mixtures has seen mat temperatures in the range of 80 -110°C, compared with common German practice of 40 to 60°C.

**COMPARISON BETWEEN GERMAN AND AUSTRALIAN SMA DESIGN APPROACH**

Germany has used SMA for over 30 years and was developed as a solution to the problem of abrasion caused by studded tyres in the winter months. The focus was to design a material having a very high deformation resistance (high stability) coupled with very good durability. These twin components resulted in what is now termed SMA. Its design is based on a methodical and systematic approach in order to ensure the desired performance is met. The German specification calls up the use of high quality materials and it is worth re-iterating the key design principles again. The design process is one of adjusting the grading to accommodate the required binder and voids content rather than the normal procedure of adjusting the binder content to suit the aggregate grading. The key steps are:

Trial mixture, complying with the grading envelope, is made using the chosen aggregates.
Laboratory mixtures are made at the target grading and at the minimum binder content.
Drainage behaviour is assessed.
Marshall specimens are made to assess voids content. If the requirements of Table 1 are **NOT MET**, then the priority change order is:
Coarse aggregate grading or content
Content and/or filler type
Content and/or stabilising additive
Binder content
The target composition is then adopted as the job material specification

In contrast, the rationale for using SMA in Australia is different and although the term SMA has been adopted, it is clear the original German design procedures, regarded as critical to achieve good performing mixtures, have not. Australia is not alone in ‘customising’ SMA to suit the local environment but the danger is that modifying the protocols invariably leads to mixtures that are borderline between success and failure. Tailoring mixtures to suit local conditions is not wrong but with a critical performance mixture such as SMA there needs to be an understanding of what the effects will be through making modifications.

Binder contents are generally lower than what is allowed in Germany and this has the added effect of leading to a more open SMA. In Germany, such mixtures would fail to meet specification and also probably fail to provide sufficient durability.

**CONCLUSIONS**

SMA is widely used in Germany and is the premium bituminous surface course used on the strategic road network. The design principles must be followed in order to achieve both a high strength and durable material. SMA is designed using the highest quality materials and, in Germany at least, specific properties must be achieved in the design process in order for the material to be accepted as SMA. It is noted that SMA is used elsewhere within Europe and is gaining ground in countries such as Australia and the USA. Further, the design principles of SMA have been modified, sometimes to the detriment of performance. The critical performance parameters of SMA have been highlighted and these are regarded crucial for the material to perform in-service. PMB’s play a leading role in ensuring good SMA performance on the major road network.

Australian SMA mixtures have been based on the German experience with some interpretation of the design to suit Australian conditions. SMA has been well received although has had both successes and failures throughout the country probably due to the differing design principles adopted. There are several specifications in existence across Australia, which are adjusted to suit the local climatic and/or traffic conditions. It is recommended that a more uniform approach be adopted to align the SMA more with the German approach and to learn from the successes and failures that have occurred.

The field compaction of SMA requires more vigilance so that the need to use vibratory rolling and multi-tyre rollers is avoided. Consideration of traffic placement on newly laid SMA should be considered prior to opening to traffic so that mat temperatures are controlled in the range 40 - 60°C, as per the German practice.

More work is required in the area of field voids if SMA is to provide an impervious layer as it is intended. Past works have shown that Australian mixtures have produced field air voids in the range of 6 to 11%. However, air voids must be reduced to 5.0% or lower to ensure there are no interconnecting air voids. It is considered this can be achieved by modification of the grading and with the addition of more binder and fibre. Consideration should be given to the increasing the rate of fibre addition to 0.4 –0.5% for specific applications to aid in the use of high binder contents, which in turn will increase the resistance of the mix to permeability and will also increase mix durability.

**REFERENCES**

[3] Technische Lieferbedingungen für Mineralstoffe im Straßenbau (Gesteinskörnungen und Werksteine im Straßenbau); TL Min-StB 2000

[4] Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Fahrbahndecken aus Asphalt, ZTV Asphalt-StB 01 (Additional technical contractual conditions and directives for the construction of roadway surfaces from asphalt)

[4a] „Merkblatt für Eignungsprüfungen an Asphalt“, Ausgabe (Code of practice for qualification tests on asphalt)


[8a] Technische Lieferbedingungen für gebrauchsfertige polymermodifizierte Bitumen, TL PmB, Ausgabe 1991 (Technical conditions of delivery for ready to use polymer-modified bitumen)- 1991 issue

[8b] Technische Lieferbedingungen für gebrauchsfertige polymermodifizierte Bitumen, TL PmB, Ausgabe 2001 (Technical conditions of delivery for ready to use polymer-modified bitumen) – 2001 issue


[12] „Neue Qualitätskriterien für Normbitumen und PmB“, Dr. H.-E. Höppel, Bitumensymposium Würzburg 1999 (New quality criteria for standard bitumens and PmB)


[16] Praktische Bewährung von Asphalt mit polymermodifizierten Bitumen, Dokumentation BP, Shell, elf und Nynas (Practical evaluation of asphalt with polmer-modified bitumen)


ACKNOWLEDGEMENTS

The assistance various industry members is greatly appreciated in the collection of information on the history of SMA use in Australia in particular:

Steve Hogan, Russell Lowe and John Patane (QDMR)
Ross Paul (VicRoads)
Bruce Hanson (BCC)
Errol Jones (formerly BCC)

AUTHOR BIOGRAPHIES

Michael Kreide, Technical Manager (Central Europe)

Michael has studied Civil Engineering and has over 20 years of experience in the field of mechanical testing, design and construction of roads. Furthermore, over the last 13 years he has specialised in the area of bitumen and asphalt testing and development of new bitumen products. Michael previously worked for the road building administration, private labs and bitumen companies in Germany.

Michael joined the BP bitumen business in 1997 as Lab Manager and since 1999 he became Technical Manager and is now responsible for all technical issues of BP Bitumen (Germany).

Mick Budija, Research Technologist – Binders and Applications

Mick has over 20 years of experience in the field of mechanical testing and over the last 15 years has specialised in the area of hot mix asphalt; this has included asphalt mix design, production and mobile road plant application. Mick has previously worked for VicRoads and for Pioneer Asphalt.

Mick joined the bitumen business of BP Australia in 1992 as the Bituminous Applications Technologist based at BP Bitumen’s Altona Regional R&D laboratory located in Melbourne. In this capacity Mick has responsibility for, asphalt mix design, slurry mix design, customer and field support.

Mick has designed numerous conventional and specialist asphalt mixtures for projects in Australia and overseas and has been involved in the design and manufacture of numerous items of customised laboratory testing equipment including the BP Slab Compactor.

Jim Carswell, Central Research – Global

Jim has over 28 years experience within the highways industry, the last 7 being at BP’s Research and Technical Centre in the UK. Prior to this, he spent 21 years at the Transport Research Laboratory UK researching bituminous materials, with particular emphasis on the role of modified binders.

Jim has presented papers at numerous international conferences, has written many external papers and articles and is active within Europe on a number of specification committees. His specialism on bituminous applications has enabled BP to promote a number of products in both new and existing markets.
Figure 1  Aggregate Grading Curve (SMA 0/11S)

Figure 2  Aggregate Grading Curve (SMA 0/8S)
Figure 3  Aggregate Grading Curve (SMA 0/5)

Figure 4  Binder drainage versus Proportion of Stabiliser (SMA 0/11)